# DANESS
# Dynamic Analysis of Nuclear System Strategies

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**Abstract** – The dynamic analysis of multiple development paths for nuclear energy systems has gained interest worldwide. Especially in the light of the different roadmap exercises that have been undertaken in the past years indicating the need for symbiotic nuclear energy systems in the longer term. The symbiosis between different nuclear reactor types and their associated fuel cycle should fulfill competing objectives for such systems, i.e. economics, environmental friendliness, resource longevity, waste management, and non-proliferation. A new code, dubbed DANESS, has been developed which allows performing such dynamic analysis of nuclear energy systems composed of multiple reactors and fuel cycle options including cross-flow of fissile material between the different components of the system. Today, the code allows mass-flow analysis and economics and is currently being extended to include life-cycle analysis data, non-proliferation metrics and non-nuclear energy sources. This paper will describe the main features of this code and will indicate the possible uses and future developments.

## I. INTRODUCTION

Nuclear energy is at a crossroad in its development. More than fifty years of research and development (R&D) in nuclear energy has given us various routes to make nuclear energy more sustainable. R&D in reactor design and operation may make new reactor designs economically attractive and safer than before. R&D in the front- and back-end of the nuclear fuel cycle made available new technologies reducing the amount of waste to be managed, shortening the long-term stewardship demanded for waste disposal, and also resulted in continuous reduction of costs in the fuel cycle.

Future nuclear energy systems will consist of various mixes of these new reactors and fuel cycle technologies. Addressing all the objectives posed by society will require integrated nuclear energy systems – so-called symbiotic nuclear energy systems - where each reactor will have a specific role to play, e.g. light water reactors (LWRs) and fast reactors (FRs) as 'workhorses' for energy production, FRs in addition as transuranic-burners or, later-on, fissile material breeding [1]. The mix present in the system will evolve over time due to new reactor technologies being developed as well as changing focuses in fuel cycle options and energy demand, e.g. from burning to breeding, electricity and hydrogen and, not at least, by the economic competitiveness with other energy sources. The time-scales involved in such evolution are long, from years to even a century. During this energy supply evolution process, several options in development may be chosen and the technical and economic analysis of these alternative options, and especially their impact over time, asks for a dynamic systems view of the whole nuclear energy system [1-2].

DANESS is an integrated nuclear process model intended for the dynamic analysis of today's and future nuclear energy systems on a fuel batch, reactor, and country, regional or even worldwide level. The model allows simulating up to 20 different reactor types and up to 20 different fuel types in one simulation. The fuel cycle consists of 21 steps in the fuel cycle chain where several fuel cycle facility technologies can be characterized in the model.

In its current version, DANESS v1.0, it is intended to deliver a systems view on future nuclear development paths. It therefore emphasizes the actinide and fission product mass flows in the system and the economics of the components and the system as a whole. Detailed isotopic compositions of fuels are not calculated but are based on associated databases of typical fuel isotopic compositions.

DANESS is aimed for use as an integrated process model for use in policy-supporting studies, technical-economic assessments of nuclear in connection to other energy sources as well as an educational tool for students, researchers and policy-makers.

## II. DESCRIPTION OF DANESS

Starting from today's nuclear reactor park and fuel cycle situation DANESS will simulate energy-demand driven nuclear energy system scenarios over time and allows the simulation of changing nuclear reactor parks and fuel cycle options. The energy demand is hereby given as an energy-demand scenario for electricity or any other energy form demanded from nuclear, e.g. hydrogen production. New reactors are introduced based on the energy demand and the economic and technological ability to build new reactors. The technological development of reactors and fuel cycle facilities is modeled to simulate the delays in technology availability. Levelized fuel cycle costs are calculated for each nuclear fuel batch for each type of reactor over time and are combined with capital cost models to arrive at bus-bar costs per reactor and, by aggregation, into a cost of energy for the whole nuclear energy system. More detailed cost analysis is performed to give an evolution of expenses for utilities, taking into account taxes, depreciation policies, average cost of capital, and others. A utility sector and government-policy model may be activated to simulate the decision-making process for new generating assets and new fuel cycle options. The government-policy model is still under development and will allow simulating different actions that governments may exert through, for instance, tax rates, regulation, R&D-funding and others. Extension to life cycle analysis data, non-proliferation metrics and ecological impact for the system as a whole and/or sub-elements of the system is foreseen in future versions of DANESS.

Figure 1 gives a schematic breakdown of DANESS. The DANESS-model is accompanied with a MS-Access database including validated mass-flow and inventory attributes for various reactor types and fuel types as well as for fuel cycle facilities. The database also contains the data on the current operating reactors worldwide and is annually updated. DANESS-simulations may therefore be based on real initial conditions on a utility, country, regional or worldwide level.

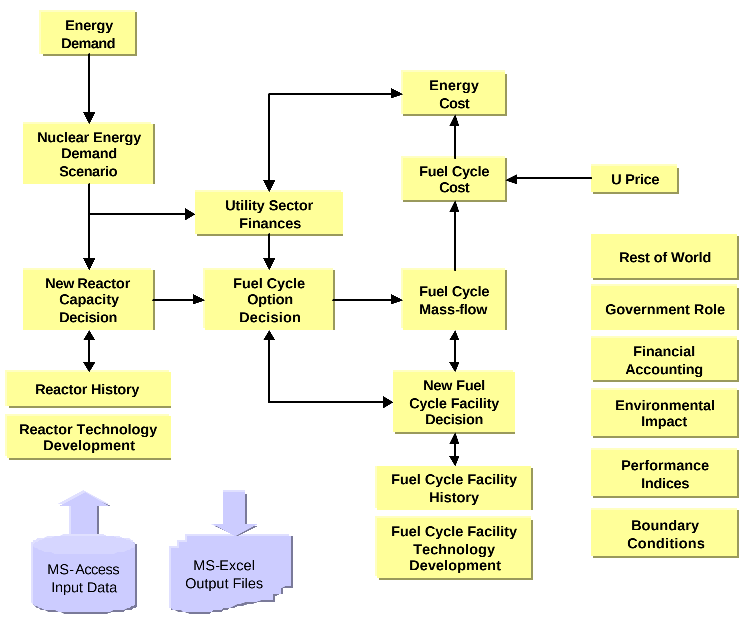


Figure 1. Schematic breakdown of DANESS.

## III. ENVISAGED APPLICATIONS

The use of DANESS is focused on scenario-analysis of different development paths for nuclear energy systems. The evolution viewpoint may be from a governmental, a utility or an R&D perspective. As an integrated process model, its intended use comprises:

- *Integrated analysis of development paths for nuclear energy*: the impact of new developments in nuclear reactor development and fuel cycle operations may be analyzed from an integrated perspective.
- *Integrated process model* for the cost-benefit analysis of specific new technologies (reactor or fuel cycle facilities) in order to guide the R&D or engineering design of new facilities.

- *Parameter scoping for new designs:* in analogy with the above use, DANESS can be used to assist in analyzing the possible impacts of new technologies in complete nuclear energy systems and help guide the R&D-effort identifying the key development drivers for new technologies and the trade-offs between these parameters.
- *Economic analysis of nuclear energy systems:* DANESS can be used as a tool to calculate today's and projected nuclear energy costs based on different development scenarios of price, technical characteristics of plant, fuel cycle operations and costs as well as impact of government actions. This analysis may be done on a short-term as well as on a long-term time horizon.
- *Government role:* governments willing to analyze the role of nuclear energy in a sustainable energy future may seek to analyze the possible policy-tools. These may be used to influence the energy sector to re-invest in nuclear energy or to change the fuel cycle option to a longer-term sustainable but economic perspective.
- *Educational use:* the ability to simulate different fuel cycle scenarios and the impact and role of different reactor types on ecological, non-proliferation and economic goals may facilitate the understanding of nuclear energy systems in nuclear engineering education as well for the broader public, including policy-makers. The architecture of the model facilitates the transparency of the simulation results.

While this list is not exhaustive, it does indicate the type of applications. The use of DANESS is not aimed at predicting the future but on helping to project and analyze – in a consistent way – the longer term outcomes from selecting alternative nuclear energy development paths.

An additional advantage of DANESS is the implementation on standard PC/Mac platforms. A typical full-scale DANESS simulation covering a time-span of 100 years calculated in time steps of one month takes about 15 to 30 minutes on a modern PC or Mac. Shorter calculation times in the order of a minute are obtained with reduced problem sizes. DANESS is currently implemented using the Ithink-Analyst software of High Performance Systems [3].

DANESS has been extensively verified with other calculations of nuclear energy systems and this verification has indicated error margins inferior to a few percent depending on the quality and detail of data delivered by the user.

## IV. DESCRIPTION OF MAIN FEATURES

Figure 1 already gave a schematic breakdown of DANESS. A short description will be given of some of the main features of DANESS.

### *IV.A Nuclear Energy Demand*

DANESS is an energy-demand driven model based on an exogenously defined energy demand scenario. This energy demand scenario may be input graphically, as a function or as tabled values. Energy demand scenarios may cover a country, region or world but may also be set as a fixed value if the user wants to simulate one reactor or a non-expanding reactor park. The DANESS-model will use the energy demand data as historic data to forecast the energy demand within a certain planning horizon. DANESS will order new reactors to match this energy demand forecast based on the forecasted operational reactor capacity, the expected energy demand and the margin for improvement of the average capacity factor of the operating reactors.

### *IV.B. New Reactor Capacity Decision & Reactor History*

A DANESS-simulation may start from an existing reactor park. The data on the existing reactor park are input from the associated DANESS database. Based on the shutdown schedules of the existing reactors and the forecasted energy demand DANESS will aim to match this demand by ordering new reactors depending on:

- the expected energy shortage in the planning horizon. The planning horizon is defined by the user or set by the economic decision making sub-model. If the expected energy shortage can not be compensated by changing the average capacity factor of the reactors (if allowed), new reactors will be considered for ordering;
- the technological readiness of the reactor type;
- the type and amount of reactors to be ordered is also based on constraints:
  - the user may give a preferred reactor park composition or the model will apply the economic decision making sub-model which will distribute the reactors ordered as a function of their bus-bar cost.
  - the availability of fissile material to fuel new reactors. In case of shortage of fissile material the model will order new fuel cycle facilities (if the user has allowed this option) or will order a limited number of reactors according the availability of fissile material.
  - if a reactor type uses two or more fuel types, e.g. LWR partially MOX-loaded or a FR with CR=1, the model will check the availability of all these

fuel types and will possibly limit the ordering of reactor types accordingly.

Once the reactor is ordered its life cycle will be followed, i.e. licensing, construction, operation, shutdown and finally decommissioning. Reactors that were ordered but that are short of fuel at the moment they are ready for start-up will be kept 'on-hold' until enough fresh fuel has been fabricated. The same applies for operating reactor capacity that may be set in 'stand-by' mode if not enough fresh reload fuel may be fabricated.

If the user has decided to allow varying the average capacity factor of reactors the DANESS-model will change this factor if momentary energy shortages occur.

The expenses at each moment in a reactor's life cycle are taken into account, i.e. capital expenses (based on a calculated economic life time, contingencies, ….), O&M and fuel cycle expenses. A levelized bus-bar cost for electricity generation is also calculated per reactor and is aggregated for the whole nuclear energy system.

### *IV.C. Technological Readiness Levels*

Each reactor type and each fuel cycle facility may follow an R&D development path consisting of 9 phases. The timing of these phases may be different for each reactor type and each fuel cycle facility and may also vary over time as a result of simulated government action, learning effects, and others. This functionality allows the user to simulate, for instance, the phased availability of fuel cycle technologies delaying the introduction of certain fuel cycle options or reactor types.

### *IV.D. Fuel Cycle Mass-Flows*

This sub-model is the most extensive one in DANESS and follows for each fuel type the mass-flows from the front to the back of the fuel cycle including waste management and disposal. A fuel fabrication demand based on the current and future reactor park triggers the demand for fissile material in front- and back-end. Time-lags modeled in the fuel cycle require that fuel fabrication be started well in advance of reactor loading and the DANESS-model takes account of all relevant time-lags in reactor and fuel ordering as well as in fuel facility capacity expansion decisions. The DANESS-model checks the availability of fissile material for the different fuel and reactor combinations and will order new fuel cycle facilities or will change the reactor park fractions or fuel cycle options according to the criteria set forward by the user.

Each fuel type may follow 21 fuel cycle steps, going from U-mining until geological disposal. Intermediate stocks of depleted uranium, enriched uranium, fresh fuel, spent fuel in different storage types, separated nuclides and nuclide compositions of mass flows (based on given data-sets) are calculated. The user may allocate separated nuclides to specific fuel types allowing cross-flows of fissile materials between fuel types and fuelling of reactors. For instance, the user may consider that separated minor actinides from reprocessing UOX are reserved for later FR-use where the plutonium may be used for LWR-MOX fabrication. Similarly, the user may consider that plutonium from FR metallic fuel reprocessing is not available for LWR-MOX fabrication but only for FRs. This functionality also allows to simulate different fuel batches in the start-up sequence of reactors or to take account of different average burn-ups or other changes in fuel characteristics.

All the characteristics of the fuels may be a function of time; so may the allocation of fuels to reactors or fuels to fuel cycle facility technologies. For instance, technological progress may induce a switch from gaseous diffusion to ultra-centrifuge enrichment technology or reprocessing of UOX may change from standard aqueous to advanced aqueous (e.g. including Np-separation). This may also be a gradual change over time. Fuel cycle facilities also have different characteristics and several technological options per fuel cycle step are available. This functionality is made feasible by the use of an innovative approach of 'allocation matrices' between reactors, fuels and fuel cycle facilities. This approach is based on an uncoupling between reactor and fuel types, as well as between fuel types and fuel cycle facilities. This allows the application of a systems-thinking approach in its broadest sense, i.e. each combination of reactor, fuel, fuel cycle facility and fuel cycle option may be simulated and this combination may change over time. For instance, for fast reactor driver and blanket fuel the user may specify that the driver fuel be reprocessed by dry reprocessing techniques (using the attributes for dry reprocessing) where the blanket fuel is reprocessed by an aqueous process with different attributes (losses, transit time, costs). Reactors, for instance LWRs, may be considered changing fuel loading over time, e.g. UOX to partial MOX-loading or fast reactors may change conversion ratio needing different fuel types for the different conversion ratios. Moreover, evolving symbiotic energy parks can be modeled wherein, e.g., LWR discharged fuel provides feedstock for fast reactors that in turn provide fissile feedstock for thermal reactors. Choosing the correct attributes for reactor, fuel and fuel cycle facilities remains the responsibility of the user.

This approach also allows to pre-set DANESS for certain applications, e.g. freezing the 'allocation-matrices' to a certain scenario allows to configure DANESS for use by less experienced DANESS-users within specific constraints or to customize DANESS for specific utilities, countries or fuel cycle options.

Figure 2 shows this basic uncoupling of the three dimensions: reactors, fuels and fuel cycle facilities. The detail of DANESS can be indicated by the attributes for reactors, fuels and fuel cycle facilities considered as shown in table 1. This version 1.0 of the DANESS-model details fuel compositions on actinide element level but does not differentiate isotopic compositions. Fission products are currently categorized as long- and short-lived.

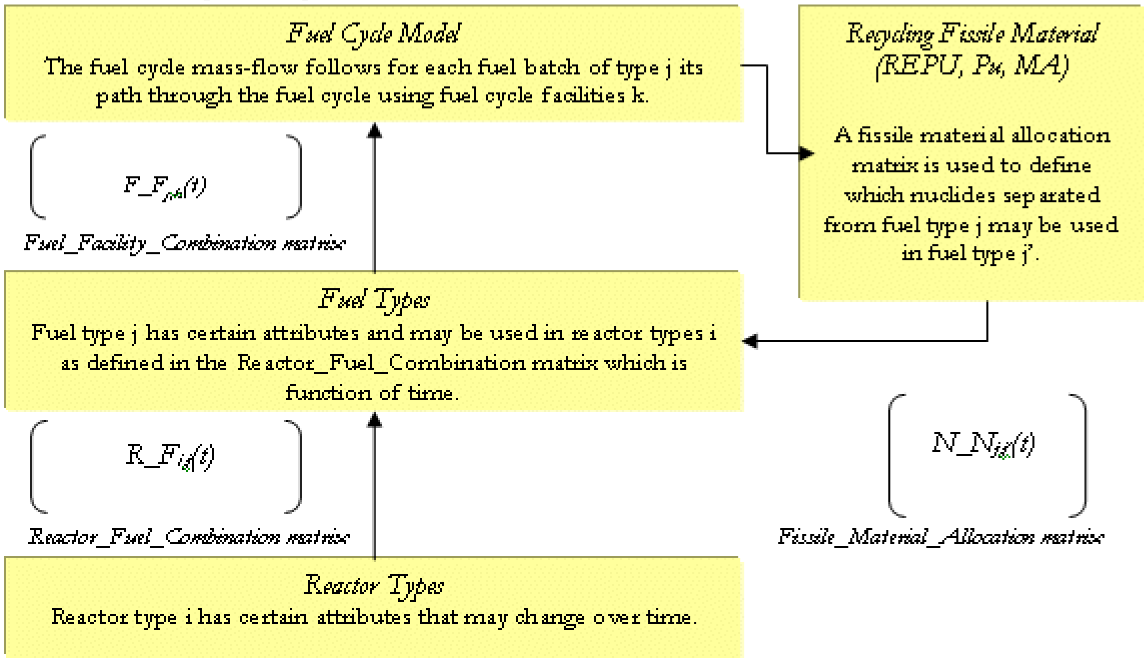


Figure 2. The Basic Architecture of DANESS Allows A High Degree of Flexibility in Combing Reactor Types, Fuel Type and Fuel Cycle Facilities.

Table 1. Attributes for Reactors, Fuels and Fuel Cycle Facilities Used in DANESS v1.0.

| Reactors | Fuels | Fuel Cycle Facilities |
|---|---|---|
| Thermal Power | Burn-up | Initial Installed Capacity |
| Electric Power | Initial U | Unit Capacity |
| Thermal efficiency | Initial REPU | Unit Cost of throughput |
| Average capacity factor | Initial DU | Cost escalation rate |
| Cycle length | Initial Enrichment | Losses in process |
| # of fuel batches | Initial Pu | Losses of U in process |
| Licensing Time | Initial MA | Losses of Pu in process |
| Construction Time | Initial Np | Losses of MA in process |
| Average Lifetime | Initial Am | Losses of Np in process |
| Overnight Construction Cost | Initial Cm | Losses of Am in process |
| Other Overnight Capital Cost | Spent U | Losses of Cm in process |
| Decommissioning Cost | Spent Enrichment | Transit time for process |
| Contingencies | Spent Pu | Average Capacity factor |
| O&M Cost | Spent MA | Licensing Time |
| Initial TRL | Spent Np | Construction Time |
| Learning coefficient costs | Spent Am | Average Lifetime |
| Learning coefficient O&M | Spent Cm | Overnight Construction Cost |
| Learning coefficient licensing | Spent FP | Other Overnight Capital Cost |
| Learning coefficient construction | Spent SLFP | Decommissioning Cost |
| Learning coefficient decommissioning | Spent LLFP | Contingencies |
| | Spent Activity | O&M Cost |
| | Decay Heat at Discharge | Initial TRL |
| | | Learning coefficient costs |
| | | Learning coefficient O&M |
| | | Learning coefficient licensing |
| | | Learning coefficient construction |
| | | Learning coefficient decommissioning |

### *IV.E. New Fuel Cycle Facility Decision & Facility History*

New fuel cycle facilities may be ordered if the forecasted demand indicates a shortage of capacity. Time-lags to order, license and construct these facilities are taken into account. The user may also prohibit the order of certain new fuel cycle facilities or may input a deployment scenario. Ordering of new reactors will take account of the timely availability of the needed fissile material based on the expected available fuel cycle capacity.

Analogous to the reactor history sub-model this sub-model traces the ordering, licensing, construction, operational status and shutdown of fuel cycle facilities. The technologies follow a technology development path covering 9 technological readiness levels where the duration of each step may be different among technologies and over time. The expenses in each stage of the life cycle are accounted for.

### *IV.F. Fuel Cycle Costing*

This sub-model calculates for each batch of fuel the associated costs for each step in the fuel cycle and consequently calculates a levelized fuel cycle cost per fuel type and per reactor type. The cost and expenses for each fuel type are accounted for while the user may also simulate the difference between owning and leasing of fuel. Unit costs for each fuel cycle step are available in a database [4-5] or may be given by the user or calculated from the fuel cycle facility sub-model using a cost-margin. Costs may be made subject to learning effects.

A uranium price sub-model may be activated to vary the uranium price according to the remaining availability of natural uranium. This sub-model takes account of expected exploration expenses, already mined uranium and expected uranium resources availability.

### *IV.G. Energy Costing*

The energy costing covers capital costs, O&M costs and fuel cycle costs. Each of those may be subject of learning effects. The financial parameters such as cost of capital, gearing, discount rate, and others are given by the user and may be function of time.

The energy costing is used in the economic decision-making – if requested by the user – to decide on allocation of new reactor orders. A 'Pythagorean Equation' distribution based on the bus-bar cost of the various reactor types and their fuel cycle options is currently used to decide on which reactors are to be ordered and which fuel cycle option to be chosen.

### *IV.H. Financial Accounting*

The financial accounting lets the user detail the cash-flows for the different owners of facilities per reactor type and/or per fuel type. Owners may be private sector or government type that is translated in, for instance, different risk-premiums used to calculate the capital charges. Transfer-pricing between facilities or between fuel types are calculated. Expenses for reactors and fuel cycle facilities are calculated based on the financial parameters set in the financial utility sector model and the government role model. The user may then recombine revenue and cost streams to make a financial balance per asset or owner.

## V. EXAMPLE OF APPLICATIONS

Two typical examples of application will be given to illustrate the diversity in applications that may be addressed with DANESS v1.0.

### *V.A Closing the Nuclear Fuel Cycle*

The US-DOE has recently started the Advanced Fuel Cycle Initiative [6] aimed at developing technologies that would close the nuclear fuel cycle for all actinides thereby alleviating the continuous need for new repositories. A significant reduction, a hundred-fold, of the radiotoxicity in the repository is also achieved allowing to drastically shorten the long-term stewardship for such repositories by better managing the heat load and radiotoxicity of the buried waste.

Several advanced nuclear fuel cycle scenarios are under consideration where a quick and comparative analysis is needed to assess the different available options and to guide decision-makers in prioritizing resources. DANESS is used by ANL to perform these kind of comparative analysis between different advanced fuel cycles with respect to the mass-flows and resulting stocks of fuel and separated materials as well as the resulting economic picture for the government and utilities. An expected nuclear energy demand growth of 2%/yr after 2010 is used to illustrate the effects of the different fuel cycle scenarios on the variables investigated. Figure 3 shows a typical result of the comparison of the amount of spent fuel disposed in repository and the actinide inventory in the fuel cycle for three scenarios. The three scenarios are nuclear phase-out, business-as-usual of the existing reactor park with new orders of LWRs and a LWR+FR type of nuclear energy system with FRs acting as TRU-burners. In this latter case, a user-defined reprocessing capacity deployment scenario was used with 5000 tHM/yr LWR-UOX reprocessing capacity in place by mid-century and a doubling by the end of the century.

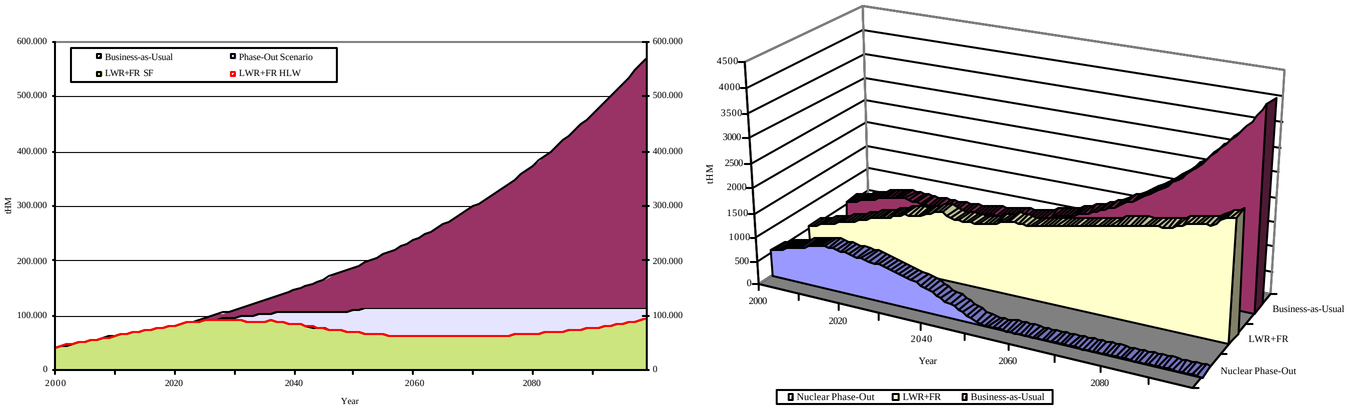


Figure 3. Comparison of the amount of spent fuel and high level waste to be disposed in repositories for three US nuclear energy system scenarios. Right figure shows the corresponding amount of actinides in the fuel cycle (i.e. out-of-reactor and out-of-repository) for the three scenarios.

### *V.B. DUPIC Nuclear Fuel Cycle Development*

Those countries having a mix of LWR and CANDU reactors might consider developing the so-called DUPIC nuclear fuel cycle. Spent LWR fuel is dry reprocessed through the use of the OREOX process where the refabricated fuel is recycled in CANDU reactors. A DANESS simulation, using unit costs as reported in literature [7], indicates the evolution of the aggregated bus-bar cost of electricity generation for a reactor park of 12 LWRs and 4 CANDUs. Figure 4 shows the evolution of the amount of spent fuel over time for this reactor park (assuming 60 years lifetime for reactors without new reactors being ordered). The levelized fuel cycle costs for the fuel for LWRs are calculated as 5.9 mills/kWhe, for CANDU-UOX 4.8 mills/kWhe and for CANDU-DUPIC fuel 6.8 mills/kWhe.

Additional information on these scenarios is available from the authors. A more elaborate use of DANESS is presented during this conference [8].

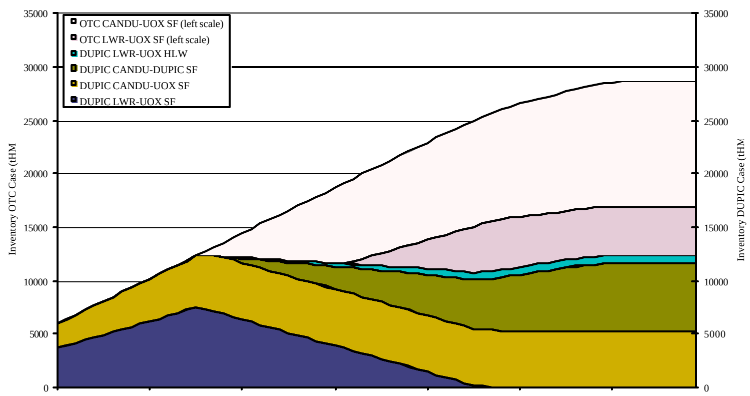


Figure 4. Spent Fuel Amount for a mixed LWR-CANDU reactor park with different fuel cycle options, i.e. once-through and DUPIC.

## VI. FUTURE DEVELOPMENTS

DANESS v1.0 is currently used in different projects. Based on this experience feedback new add-ins will be developed in the coming years. Developments currently under consideration are:

- Inclusion of isotopic compositions (isotopic mass tracking).

- Extending the cost database and implementation of scaling laws for these costs for reactor and fuel cycle facilities.
- Refinement of economic decision model by including market mechanisms and specific models for financial parameters, e.g. risk premium, …
- Integration of macro-economic energy balance
- models including non-nuclear energy sources.
- Calculation of radiotoxicity for the disposed waste.
- Macro-economic model for market competition with non-nuclear energy resources.
- Monte Carlo analysis with extended sensitivity analysis tools.

## VII. CONCLUSION

A new code DANESS v1.0 for the dynamic analysis of complex nuclear energy systems has been developed. This code allows the user to simulate all aspects of a varying mix of reactor and fuel types including the economic performance of such systems.

Application of DANESS in various applications has shown that results can be within a few percent of the results obtained with more detailed, but non-integrated, codes. A major advantage of DANESS is that all the calculations are performed within one integrated code with an easy-to-use user interface and link of the results to MS-Excel. In addition, the short calculation time of about 15 minutes for a 100-year simulation allows users to assess multiple options before embarking on more detailed studies.

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